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Aquatic Assemblages of the Highly Urbanized Santa Ana River Basin, California

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Abstract.—We assessed the structure of periphyton, benthic macroinvertebrate, and fish assemblages and their associations with environmental variables at 17 sites on streams of the highly urbanized Santa Ana River basin in Southern California. All assemblages exhibited strong differences between highly urbanized sites in the valley and the least-impacted sites at the transition between the valley and undeveloped mountains. Results within the urbanized area differed among taxa. Periphyton assemblages were dominated by diatoms (>75% of total taxa). Periphyton assemblages within the urbanized area were not associated with any of the measured environmental variables, suggesting that structure of urban periphyton assemblages might be highly dependent on colonization dynamics. The number of Ephemeroptera, Trichoptera, and Plecoptera (EPT) taxa included in macroinvertebrate assemblages ranged from 0 to 6 at urbanized sites. Benthic macroinvertebrate assemblages had significant correlations with several environmental variables within the urban area, suggesting that stream size and permanence were important determinants of distribution among the species able to survive conditions in urban streams. Only 4 of 16 fish species collected were native to the drainage. Fish assemblages of urbanized sites included two native species, arroyo chub *Gila orcuttii* and Santa Ana sucker *Catostomus santaanae,* at sites that were intermediate in coefficient of variation of bank-full width, depth, bed substrate, and water temperature. Alien species dominated urbanized sites with lesser or greater values for these variables. These results suggest that urban streams can be structured to enhance populations of native fishes. Continued study of urban streams in the Santa Ana River basin and elsewhere will contribute to the basic understanding of ecological principles and help preserve the maximum ecological value of streams in highly urbanized areas.

Introduction

As human population growth continues, urbanization and its effects on water quality and water quantity will increase in importance to biota, including humans, dependent on water resources (Naiman et al. 1995; Baer and Pringle 2000). Effects of urbanization on water quality and ecological conditions within watersheds are and will likely remain important scientific and policy issues in the foreseeable future (Grimm et al. 2000).

Urbanization can have a wide range of chemical and physical effects on stream systems (Klein 1979; Heany and Huber 1984). Increased storm water runoff due to large areas of impermeable surface can increase the frequency and magnitude of storm flows (Arnold et al. 1982; Booth and Jackson 1997; Trimble 1997). Base flows can decline because of groundwater pumping and reduced recharge (Klein 1979; Finkenbine et al. 2000). Sediment regime, streambed composition, and stream channel morphology may change in response to altered hydrology and flood management practices (Arnold et al. 1982; Booth 1990, 1991; Booth and Jackson 1997; Finkenbine et al. 2000). Loss of riparian vegetation can lead to higher water temperatures through loss of shading (Booth 1991; Belt and O'Laughlin 1994; LeBlanc et al. 1996), loss of habitat for fish (Martin et al. 1986; Finkenbine et al. 2000), and changes in trophic processes (Kellar and Swanson 1979; Vannote et al. 1980). Urban runoff and treated wastewater may contain

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elevated levels of nutrients, pesticides, organic chemicals, and heavy metals (Klein 1979; Heany and Huber 1984; Field and Pitt 1990; Ahel et al. 2000; Lieb and Carline 2000; Shinya et al. 2000) that may affect aquatic biota.

Habitat and water quality alterations associated with urbanization have been linked to changes in aquatic biota. Early studies focused on effects of discharges from wastewater treatment plants on aquatic biota, but more recent studies have focused on other effects of urbanization. Urban stormwater runoff has been recognized as an important factor affecting biota (Heany and Huber 1984), as have hydrologic and land use changes associated with urbanization (Weaver and Garman 1994; Wichert 1994, 1995; Wang et al. 2000; Finkenbine et al. 2000; Sonneman et al. 2001; Walsh et al. 2001).

A common objective of many urbanization studies is to identify the level of urban land use in relatively natural watersheds that results in detectable degradation of aquatic communities. Such effects often occur at relatively low levels of urbanization (e.g., 10% of impervious surface, Limburg and Schmidt 1990; Booth and Jackson 1997; Wang et al. 2000; Wang and Lyons 2003). Although such information is important for understanding urban streams in the early stages of degradation, the information may not be useful in already developed, highly urbanized areas (Booth et al. 2002), especially in arid climates. For example, in the arid southwestern United States, many urban streams are channelized to transport large flows during low frequency, but large floods or natural surface flows are partially or completely replaced by discharges of treated wastewater or urban runoff. Managing such highly urbanized streams for maximum ecological integrity requires an understanding of ecological processes affecting them. The objective of this paper is to characterize the periphyton, benthic macroinvertebrate, and fish assemblages of selected streams in the highly urbanized Santa Ana River basin of Southern California and examine their relations with environmental variables. This general ecological approach is complementary to the metric-based assessment of the specific effects of stream channelization and water source on periphyton and benthic macroinvertebrates by Burton et al. (2005, this volume).

Study Area

The Santa Ana River basin (Figure 1) is the largest stream system in Southern California, with an area of about 6,900 km^2. The basin presently has a population of more than 4.5 million people, and the population is expected to increase to almost 7 million people by 2025 (Santa Ana Project Watershed Authority 2003). The basin is divided between two ecoregions, the Southern California Coastal Plains and Hills and the Southern California Coastal Mountains. Most urban and agricultural land uses occur in the valleys and coastal plains of the Southern California Coastal Plains and Hills ecoregion. This area is more than 70% urban, and population density is about 1,160 people/km^2. Mountains of the Southern California Coastal Mountains ecoregion are generally too steep and unstable for development and remain open space (primarily forest and other natural vegetation), largely in national forests. Overall, land use in the basin is about 35% urban, 10% agricultural, and 55% open space. The basin has a Mediterranean climate, characterized by hot, dry summers and cool, wet winters. Average annual precipitation ranges from 25 to 60 cm in the coastal plains and inland valleys, and from 60 to 122 cm in the San Gabriel and San Bernardino mountains (U.S. Army Corps of Engineers 1994).

The hydrologic system of the basin has been highly altered, especially in the lowlands. In the mountains, the streams are relatively unaltered except for intense recreational use, including roads and housing, and some diversions for hydropower on the Santa Ana River. At the transition from mountains to valley, most streams are diverted directly to public drinking water supplies or are diverted to groundwater-recharge facilities (Figure 1). Groundwater is subsequently withdrawn for various urban uses. As a result of these alterations to the system and the natural Mediterranean climate, streams generally do not flow onto the valley floor, except during large floods that exceed the capacity of diversions.

Flow is reestablished in many low-elevation valley streams by various combinations of urban runoff, discharges from wastewater treatment plants (Figure 1), or groundwater forced upward by faulting or bedrock outcrops. Urban runoff includes water from rainfall runoff, landscape irrigation, and other residential and commercial activities. Water imported from outside the basin is occasionally discharged to a stream and further downstream is diverted for groundwater recharge. In some cases, urban runoff and treated wastewater have established perennial flows in stream channels that were historically intermittent or ephemeral. In addition to these changes in water source, many streams have been channelized and some concrete-lined for flood control.

Alterations in land use, hydrology, and stream

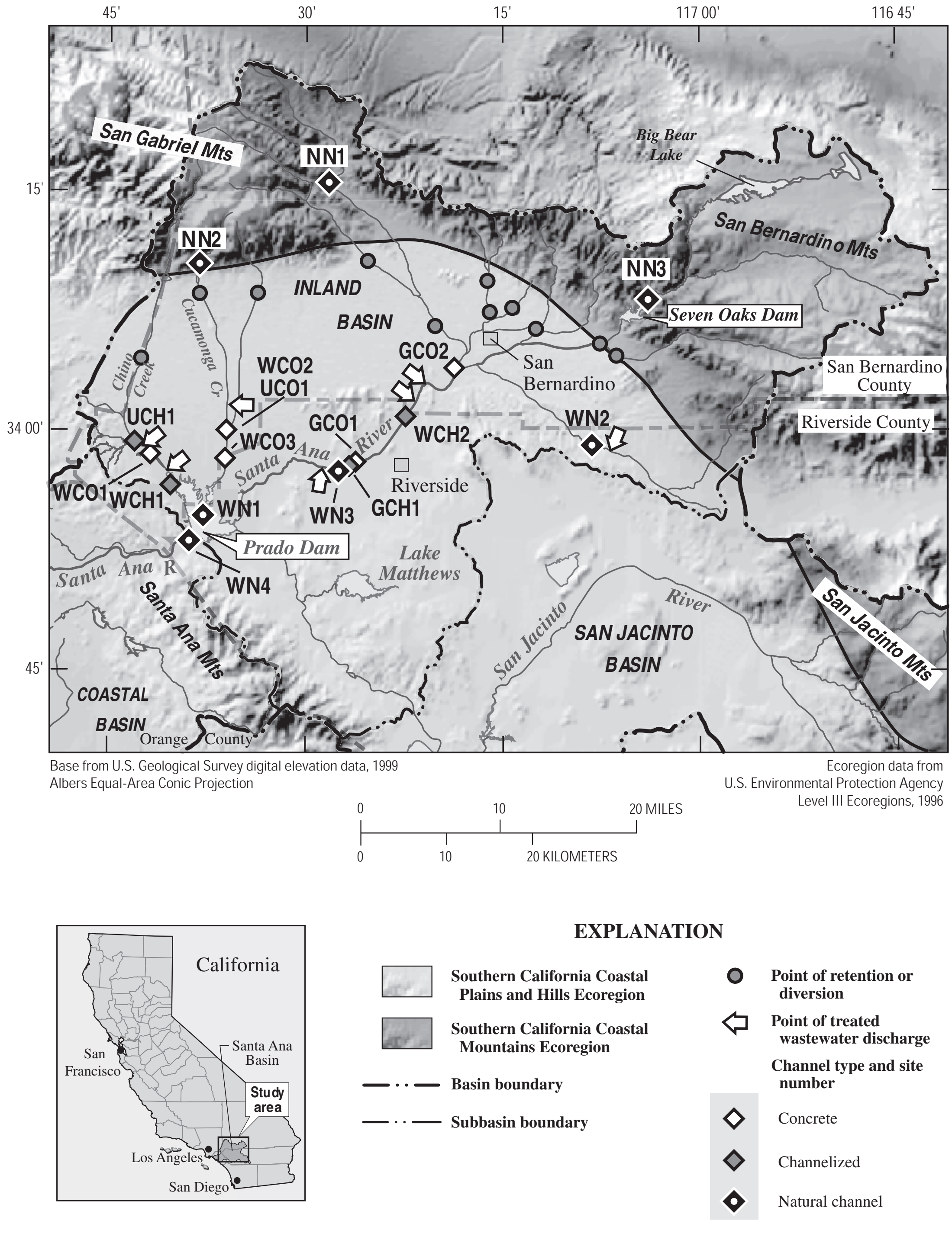

FIGURE 1. Location and site map for the Santa Ana River basin, California. See Table 1 for site names. The first letter of the site code denotes water source (N, natural; G, urban impacted groundwater; U, urban runoff; W, treated wastewater). The remaining letters denote channel type (N, natural; CH, channelized but unlined; CO, concrete-lined).

morphology have had significant impacts on ecological conditions. Terrestrial habitat has been converted to urban land uses. Riparian vegetation has been removed or extensively altered. The natural seasonal and annual variations in streamflow have been disrupted. Deliberately and accidentally introduced alien species have invaded the disturbed terrestrial and aquatic habitats. Toxic substances, such as pesticides, are now commonly found in both surface- and groundwater. These changes have led to declines in populations of various biota, including aquatic species. In aquatic systems, the most information exists for fishes. Populations of anadromous Pacific lamprey *Lampetra tridentata* and steelhead rainbow trout *Oncorhynchus mykiss* have been extirpated from most southern California streams (Swift et al. 1993). Native freshwater resident species have also declined (Swift et al. 1993), including Pacific brook lamprey *Lampetra pacifica* (likely extirpated), prickly sculpin *Cottus asper*, threespine stickleback *Gasterosteus aculeatus*, arroyo chub *Gila orcuttii*, speckled dace *Rhinichthys osculus*, and Santa Ana sucker *Catostomus santaanae*. Santa Ana sucker and several populations of threespine stickleback have been listed as threatened or endangered under federal or state endangered species legislation.

Methods

Study Design

Seventeen sites were selected to represent the available combinations of water source (natural, urban runoff, human impacted groundwater, and treated wastewater) and channel type (natural, channelized with natural bottom, and concrete-lined) available in the lower urbanized part of the basin (Table 1). There were no sites with little urban land use in the lowlands; therefore, three sites (sites NN1, NN2, and NN3) were located near the interface with the uplands to represent least-impacted conditions (Table 1; Figure 1). These three sites were located on streams with natural channels and water sources.

Measurements of Environmental Variables

Because of the complex hydrology, basin area and percent urban land use were calculated using two methods. First, they were calculated based on the natural, topographical drainage basin. Second, they were calculated based on the actual contributing area as defined by the existing urbanized hydrology. For the three least-impacted sites, these areas are the same. When a stream receives 100% treated wastewater, the contributing basin area has no meaning because water emerges from a pipe and urban land use is necessarily 100% because all of the water is from urban uses. Basin area and urban land use were determined using geographic information system databases.

Water samples for analysis of dissolved concentrations of major ions, nutrients, silica, and pesticides were collected once, when algae samples were collected (see below), using standard U.S. Geological Survey (USGS) protocols (Shelton 1994). Field measurements of specific conductance, pH, water temperature, dissolved oxygen, and discharge were made at each site visit. Analyses of dissolved concentrations of major ions, nutrients, and pesticides were conducted at the USGS, National Water Quality Laboratory (NWQL), Denver, Colorado.

Habitat variables (Table 2) were measured at each of 11 transects within each sampling reach (Fitzpatrick et al. 1998). Reaches ranged from 150 m for small streams and concrete-lined channels to 900 m for larger streams. Habitat variables were measured at the end of the study, after the benthic macroinvertebrate artificial substrates had been collected (see below).

Collections of Biota

Periphyton and benthic macroinvertebrate samples were collected between July and September 2000. Artificial substrates were used to decrease the effect of different substrate types among sites (cobbles, sand, concrete) and facilitate comparisons between sites (Aloi 1990; Lowe and Pan 1996). Unglazed clay tiles (approximately 7.5 × 7.5 cm) attached to concrete paving blocks were used to collect periphyton. Four paving blocks with two tiles each were placed at each site. Water depth and mean water column velocity were measured at each paving block when substrates were deployed and when they were collected. After a 2-week colonization period, the clay tiles were removed from the paving blocks. Periphyton was collected and processed using the top-rock scrape method (Moulton et al. 2002). Samples were preserved in 4% formalin. Periphyton taxa were identified and enumerated at the Philadelphia National Academy of Science according to Charles et al. (2002). Periphyton taxa were identified to species in most cases.

Artificial substrates for benthic macroinvertebrates consisted of a section of bristled plastic doormat (ap-

TABLE 1. Site name, site code, drainage area, urban land use, major water source, channel type and population density for sites sampled in the Santa Ana River basin, summer 2000. Drainage area and urban land use are reported for both the topographical and contributing basin. Population density is presented for the contributing basin only.

		Topographical basin		Contributing basin				
Station name	Site code[a]	Drainage area (km^2)	Urban land use (%)	Major water source[b]	Channel type[c]	Drainage area (km^2)	Urban land use (%)	Population density (people/km^2)
Cajon Creek below Lone Pine	NN1	145	4	N	N	145	4	8
Cucamonga Creek near Upland	NN2	26	0	N	N	26	0	2.5
Santa Ana River at upper powerhouse	NN3	398	5	N	N	398	5	18
Sunnyslope Creek in regional park	GCH1	19	53	G	CH	19	53	872
Sunnyslope Creek near Rubidoux Nature Center	GCO1	19	52	G	CO	19	52	869
Warm Creek near San Bernardino	GCO2	32	94	G	CO	32	94	1,888
Little Chino Creek above pipeline	UCH1	16	46	U	CH	16	46	555
Cucamonga Creek at Chino Avenue, main channel	UCO1	180	58	U	CO	132	80	1,459
Mill Creek near Splatter S duck ponds	WN1	234	52	W	N	186	63	1,117
San Timoteo Creek near Eastside Ranch	WN2	141	20	W	N	NA[d]	100[e]	NA[d]
Santa Ana River at MWD crossing	WN3	2,136	25	W	N	960	49	727
Santa Ana River below Prado Dam	WN4	3,726	32	W	N	2,394	45	689
Chino Creek below Pine Road	WCH1	259	51	W	CH	191	69	1,515
Santa Ana River above Riverside Road	WCH2	1,918	21	W	CH	743	46	686
Chino Creek above Central Avenue	WCO1	234	55	W	CO	155	78	1,684
Cucamonga Creek at Chino Avenue, wastewater channel	WCO2	180	65	W	CO	NA[d]	100[e]	NA[d]
Cucamonga Creek near Mira Loma	WCO3	208	56	W	CO	160	72	1,277

[a] The site code is composed of the one letter water source code, followed by the channel type code and a numerical identifier.
[b] N, natural; G, urban impacted ground water; U, urban runoff; W, treated wastewater
[c] N, natural; CH, channelized but unlined; CO, concrete-lined
[d] Contributing area is not applicable because all flow in the channel comes from a wastewater treatment plant.
[e] Urban land use is 100% because all flow in the channel comes from wastewater treatment plant.

TABLE 2. The 14 environmental variables measured in the Santa Ana River basin, summer 2000, including the method used to measure the variable and the reason the variable was considered important.

Variable	Method	Reason for measurement
Discharge (m^3/s)	Gaging station or instantaneous measurement	Stream size
Gradient (m/km)	Vertical drop along stream reach	General conditions
Channel width (m)	Mean wetted channel width at 11 equidistant cross-channel transects	Stream size
Coefficient of variation of bank-full width (%)	Coefficient of variation of bank-full width measured at 11 transects	Variability in stream width (channelization)
Open canopy (degrees)	Mean degrees of arc of sky (180 maximum) unobstructed by objects measured at 11 transects	Shading
Depth (m)	Mean of depths measured at three points along each of the 11 transects	General conditions
Coefficient of variation of depth (%)	Coefficient of variation of depths measured at three points along each of the 11 transects	Variability in depth (channelization)
Bed substrate	Mean dominant substrate type[a] measured at three points along each of the 11 transects	General conditions and channelization
Specific conductance (μS/cm)	Electronic meter	General water quality
Water temperature (°C)	Electronic meter	General conditions
Pesticides (number detected)	Analysis of water samples	Urbanization
Nitrite + Nitrate (mg/L as N)	Analysis of water samples	Urbanization and conditions for periphyton growth
ortho-Phosphate (mg/L as P)	Analysis of water samples	Urbanization and conditions for periphyton growth
Silica (mg/L)	Analysis of water samples	Conditions for diatom growth

[a] The dominant substrate was characterized as: 1, concrete; 2, silt, mud, or detritus; 3, sand (>0.063—2 mm); 4, fine/medium gravel (>2—16 mm); 5, coarse gravel (>16—32 mm); 6, very coarse gravel (>32—64 mm); 7, small cobble (>64—128 mm); 8, large cobble (>128—256 mm); 9, small boulder (>256—512 mm); 10, large boulder (>512 mm), irregular bedrock, irregular hardpan, or irregular artificial surface (Fitzpatrick et al. 1998).

proximately 15 × 15 cm) and an 18 cm length of 3.2-cm diameter polyvinyl chloride (PVC) pipe wrapped three times with plastic fencing (1.9-cm mesh) attached to a concrete paving block (see Figure 2 in Burton et al. 2005). This combination of materials provided a wide variety of habitats for colonization. Four substrates were placed at each site. Water depth and mean water column velocity were measured at each paving block when the substrates were deployed and when they were collected. Up to three substrates were removed after a 6-week colonization period. A 500-μm-mesh net was placed downstream of the substrate to collect any invertebrates dislodged in the removal process. The doormat and PVC pipe were removed from the paving block, and placed in a bucket. The doormat, PVC pipe, and fencing were scrubbed and inspected to remove invertebrates. Any material collected in the net was added to the sample. The sample was rinsed in a 500-μm sieve and preserved in 10% formalin (Moulton et al. 2002). Invertebrates were identified and enumerated at the NWQL following protocols for a 100-organism fixed count (Moulton et al. 2000). A 100-organism fixed count was used based on assessment of results from test substrates deployed the previous year and other sampling at the sites (Carmen Burton, unpublished data). Benthic macroinvertebrates were generally identified to genus. Some taxa, particularly noninsects, were identified at higher levels of taxonomy.

Fishes were primarily collected using single-pass electrofishing, which is generally adequate to document species richness in structurally simple channels (Meador et al. 2003). Small dip nets were used to collect fish in some very shallow concrete channels.

Seines (6-mm mesh) were used at one site (WN4) to supplement electrofishing. Fish were identified to species, counted, and released.

Data Analysis

More than 30 physical variables and more than 80 chemical variables, including concentrations of dissolved nutrients, major ions, and pesticides, were measured at the sites; however, many were redundant. Principle components analysis (PCA) and correlation analysis were used to identify a reduced set of 14 variables (Table 2) that captured the variability in physical habitat and water chemistry among the 17 sites. These variables were used in all subsequent statistical analyses. All variables were examined for normality, using normal probability plots. Discharge, channel width, dissolved concentration of nitrite + nitrate, and dissolved concentration of ortho-phosphate were log transformed to improve normality. A PCA was conducted on the 14 environmental variables to assess general environmental gradients among the sites. Only PCA axes with eigenvalues greater than one were retained for interpretation. Site scores on the first two PCA axes were plotted.

Periphyton and benthic macroinvertebrate assemblages were characterized using correspondence analysis (CA) or detrended correspondence analysis (DCA). Periphyton analyses were conducted on density (cells/cm^2), biovolume (cell volume/cm^2), and percent density and biovolume. Results were similar and only those for density are discussed. Benthic macroinvertebrate analyses used density data (organisms/m^2). Analyses were conducted using $\log_{10}(X + 1)$ transformed data. Only species found at two or more sites were included in analyses. This was a compromise between the value of rare species in separating sites (Cao et al. 2001) and the level of confidence that a species is collected if present. Complete species lists are available from the authors.

Relationships of benthic macroinvertabrate and periphyton assemblages with environmental variables were evaluated using indirect gradient analysis. Site scores on the first two ordination axes (CA or DCA) were correlated (Pearson's) with the 14 selected environmental variables. We also correlated site scores on the first two ordination axes with several metrics of the periphyton and macroinvertebrate assemblages. These metrics were calculated based on all species collected, varied with water source and channel type, and correlated with environmental variables in an independent analysis of these data (Burton et al. 2005). The periphyton metrics were number of taxa, number of diatom taxa, total density, diatom density, biovolume of blue-green algae, biovolume of green algae, percentage of nitrogen heterotrophic diatoms, percentage of eutrophic diatoms, and percentage of pollution intolerant diatoms. The macroinvertebrate metrics were number of taxa, number of Ephemeroptera, Trichoptera, and Plecoptera (EPT) taxa, number of trichoptera taxa, number of nonchironomid dipteran taxa, total density, trichoptera density, oligochaete density, density of orthoclad chironomids, noninsect density, shredder density, filterer density, and mean Environmental Protection Agency (EPA) species tolerance (Barbour et al. 1999) at the site. All variables were examined for normality, using normal probability plots. When needed, data were $\log_{10}(X + 1)$ to improve normality.

Fish presence/absence data were analyzed by group average cluster analysis of Jaccard similarities. This analysis is conservative and was chosen to avoid problems associated with inaccurate assessments of relative abundance that might occur with single-pass electrofishing. Differences in environmental variables among fish site groups were determined with analysis of variance (ANOVA). Subsequent pair-wise tests (Tukey Method) were performed for variables with significant ANOVA results.

Results

Environmental Variables

The sites varied widely for the 14 environmental variables (Table 3). A PCA of the 14 environmental variables resulted in four axes with eigenvalues greater than 1 (Table 4). These PCA axes accounted for 81% of the variance in the data. The first 2 PCA axes accounted for most of the variance (57%). Least-impacted and urban sites were clearly separated along PCA axis 1 (Figure 2). Least-impacted sites had higher channel gradients, more complex channels, larger bed substrate, lower water temperatures, less open canopy, fewer pesticides, and lower concentrations of nitrite + nitrate than urban sites. The second PCA axis separated urban sites based on discharge, depth, and ortho-phosphate concentrations (Figure 2). Sites with wastewater and a natural or channelized channel had high scores on PC axis 2 (>0). Sites with low scores (<0) had concrete channels with a mixture of water types. The third PCA axis indicated that sites with wider channels had lower specific conductance and silica concentrations (Table 4). The fourth PCA axis

TABLE 3. Values of 14 environmental variables for study sites in the Santa Ana River basin, summer 2000.

Station name	Site code	Discharge (m^3/s)	Reach gradient (m/km)	Channel width (m)	CV[a] of bank-full width (%)	Open canopy (degrees)	Depth (m)	CV[a] of depth (%)	Bed Substrate[b]	Number of pesticides	Specific conduct-ance (µS/cm)	Water temp-erature (°C)	Nitrate + nitrate (as N, mg/L)	Ortho-phosphate (as P, mg/L)	Silica (mg/L)
Cajon Creek below Lone Pine	NN1	2.8	0.009	3.8	38	79	0.10	65	4.9	2	804	22.5	1.02	<0.01	20.84
Cucamonga Creek near Upland	NN2	1.0	0.036	3.7	33	10	0.10	56	7.0	0	343	19.0	0.19	<0.01	24.12
Santa Ana River at upper power-house	NN3	1.1	0.039	7.5	32	88	0.19	61	8.3	0	286	20.0	<0.05	<0.01	20.55
Sunnyslope Creek in regional park	GCH1	2.5	0.006	1.8	23	21	0.26	53	3.0	5	984	26.0	10.41	<0.01	31.79
Sunnyslope Creek near Rubidoux Nature Center	GCO1	2.3	0.001	5.3	5	150	0.14	17	1.7	5	943	30.0	10.50	<0.01	33.43
Warm Creek near San Bernardino	GCO2	0.8	0.002	3.8	0	109	0.05	39	1.0	3	993	29.5	0.25	<0.01	21.64
Little Chino Creek above pipeline	UCH1	2.0	0.004	5.1	27	157	0.20	45	4.1	6	1,250	24.5	1.12	0.09	28.33
Cucamonga Creek at Chino Avenue, main channel	UCO1	2.4	0.013	6.2	0	155	0.04	54	1.0	6	544	30.5	0.62	0.14	21.66
Mill Creek near Splatter S duck ponds	WN1	25.2	0.001	10.9	14	60	0.33	48	3.1	2	810	23.5	6.16	2.07	21.77

TABLE 3. Continued.

Station name	Site code	Discharge (m^3/s)	Reach gradient (m/km)	Channel width (m)	CV[a] of bank-full width (%)	Open canopy (degrees)	Depth (m)	CV[a] of depth (%)	Bed Substrate[b]	Number of pesticides	Specific conductance (µS/cm)	Water temperature (°C)	Nitrate + nitrate (as N, mg/L)	Orthophosphate (as P, mg/L)	Silica (mg/L)
San Timoteo Creek near Eastside Ranch	WN2	4.8	0.013	2.0	15	44	0.20	27	4.1	4	872	28.0	22.78	3.9	26.56
Santa Ana River at MWD crossing	WN3	67.0	0.003	42.4	24	142	0.12	36	3.0	5	927	31.5	5.71	0.91	24.28
Santa Ana River below Prado Dam	WN4	190.0	0.013	17.0	21	61	0.64	39	5.9	7	965	23.5	5.65	0.964	21.53
Chino Creek below Pine Road	WCH1	24.1	0.003	7.6	21	127	0.43	53	4.4	10	841	24.0	3.92	1.57	21.31
Santa Ana River above Riverside Road	WCH2	56.9	0.003	14.1	9	117	0.21	29	4.4	3	807	28.0	3.43	1.63	25.20
Chino Creek above Central Avenue	WCO1	13.2	0.004	24.4	6	161	0.05	27	1.0	5	670	31.0	3.14	1.00	21.60
Cucamonga Creek at Chino Avenue, wastewater channel	WCO2	36.2	0.011	7.6	0	123	0.15	56	1.1	4	709	29.0	6.85	0.79	23.64
Cucamonga Creek near Mira Loma	WCO3	31.0	0.009	20.0	0	156	0.10	30	1.0	5	730	27.0	7.82	1.05	23.15

[a] CV, coefficient of variation.

[b] The dominant substrate was characterized as: 1, concrete; 2, silt, mud, or detritus; 3, sand (>0.063—2 mm); 4, fine/medium gravel (>2—16 mm); 5, coarse gravel (>16—32 mm); 6, very coarse gravel (>32—64 mm); 7, small cobble (>64—128 mm); 8, large cobble (>128—256 mm); 9, small boulder (>256—512 mm); 10, large boulder (>512 mm), irregular bedrock, irregular hardpan, or irregular artificial surface (Fitzpatrick et al. 1998).

TABLE 4. Loadings of original variables on principal component analysis (PCA) axes derived from PCA of the 14 environmental variables for sites in the Santa Ana River basin, summer 2000. Loadings greater than 0.5 are bolded.

Variable	PCA axis 1	PCA axis 2	PCA axis 3	PCA axis 4
Discharge (m^3/s)[a]	**0.51**	**0.70**	–0.39	–0.02
Gradient (m/km)	**–0.84**	<0.01	–0.22	–0.27
Channel width (m)[a]	0.43	0.28	**–0.71**	0.07
Coefficient of variation of bank-full width (%)	**–0.71**	0.37	0.23	0.25
Open canopy (degrees)	**0.60**	–0.38	–0.42	0.38
Depth (m)	0.02	**0.89**	0.17	0.22
Coefficient of variation of depth	**–0.73**	0.04	–0.09	0.36
Bed substrate[b]	**–0.78**	0.50	0.06	0.01
Specific conductance (µS/cm)	**0.59**	0.15	**0.56**	0.40
Water temperature (°C)	**0.84**	–0.40	–0.09	–0.09
Pesticides (number detected)	**0.64**	0.27	0.11	**0.51**
Nitrite + Nitrate (mg/L as N)[a]	**0.64**	0.40	0.38	–0.42
ortho-Phosphate (mg/L as P)[a]	0.46	**0.60**	–0.16	–0.45
Silica (mg/L)	0.26	–0.19	**0.81**	–0.15
Percent variance explained by PC axis	38	19	15	9

[a] Variable log transformed for analysis.

[b] The dominant substrate was characterized as: 1, concrete; 2, silt, mud, or detritus; 3, sand (>0.063—2 mm); 4, fine/medium gravel (>2—16 mm); 5, coarse gravel (>16—32 mm); 6, very coarse gravel (>32—64 mm); 7, small cobble (>64—128 mm); 8, large cobble (>128—256 mm); 9, small boulder (>256—512 mm); 10, large boulder (>512 mm), irregular bedrock, irregular hardpan, or irregular artificial surface (Fitzpatrick et al. 1998).

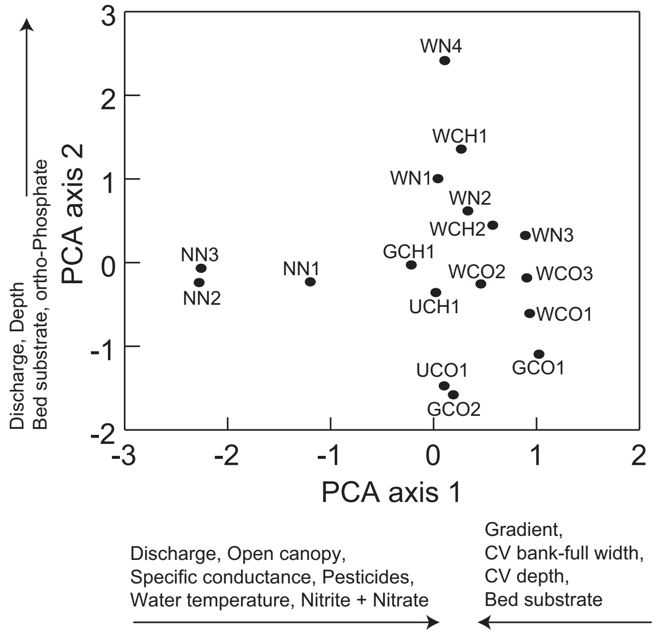

FIGURE 2. Site scores on the first two axes of a principal components analysis of 14 environmental variables measured at 17 sites in the Santa Ana River basin, summer 2000. See Table 1 for site codes. The first letter of the site code denotes water source (N, natural; G, urban impacted groundwater; U, urban runoff; W, treated wastewater). The remaining letters denote channel type (N, natural; CH, channelized but unlined; CO, concrete-lined).

summarized remaining variance in the number of pesticides detected (Table 4).

Periphyton

Artificial substrates collected a total of 62 algae taxa that were present at 2 or more sites (Table 5). Based on all taxa collected, 12–36 algae taxa were present from individual sites (Table 6). Diatoms were the dominant group contributing from 78% to 100% of the taxa found at each site. Both green algae and blue-green algae contributed from 0 to 3 taxa per site. Diatoms also tended to dominate percent density (27–100%) and biovolume (5–100%), with some exceptions. Percent density of blue-green algae was greater than diatoms at Mill Creek (42%), one site on

TABLE 5. Algae taxa (with species codes) collected from more than one site from artificial substrates in the Santa Ana River basin, summer 2000.

Species code	Taxon
	Chrysophyta (diatoms)
1	*Achnanthes exigua* Grunow
2	*Achnanthes exigua* var. *heterovalva* Krasske
3	*Achnanthes lanceolata* (Brébisson in Kützing) Grunow
4	*Achnanthes pusilla* (Grunow) DeToni
5	*Achnanthes lanceolata* subsp. *frequentissima* Lange-Bertalot
6	*Amphora veneta* Kützing
7	*Amphora inariensis* Krammer
8	*Caloneis bacillum* (Grunow) Cleve
9	*Cocconeis placentula* var. *lineata* (Ehrenberg) Van Heurck
10	*Cocconeis placentula* var. *euglypta* (Ehrenberg) Cleve
11	*Cocconeis pediculus* Ehrenberg
12	*Cyclotella meneghiniana* Kützing
13	*Cymbella affinis* Kütz.
14	*Cymbella* sp.1 JCK
15	*Fragilaria crotonensis* Kitton
16	*Gomphoneis olivaceum* (Lyngb.) P. Dawson ex Ross & Sims
17	*Gomphonema affine* Kütz.
18	*Gomphonema parvulum* (Kütz.) Kütz.
19	*Gomphonema minutum* (Ag.) Ag.
20	*Gomphonema kobayasii* Kociolek & Kingston
21	*Navicula atomus* (Kütz.) Grun.
22	*Navicula minima* Grun.
23	*Navicula seminulum* Grun.
24	*Navicula tripunctata* (O. F. Müll.) Bory
25	*Navicula decussis* Østr.
26	*Navicula tenelloides* Hust.
27	*Navicula viridula* var. *rostellata* (Kütz.) Cl.
28	*Navicula veneta* Kütz.
29	*Navicula cryptotenella* L.B. in Kramm. & L.-B.
30	*Navicula subminuscula* Mang.
31	*Navicula erifuga* Lange-Bert.
32	*Navicula recens* Lange-Bert.
33	*Navicula* sp.1 ANS NAWQA DW
34	*Nitzschia amphibia* Grun.
35	*Nitzschia dissipata* (Kütz.) Grun.
36	*Nitzschia fonticola* Grun.
37	*Nitzschia frustulum* (Kütz.) Grun.
38	*Nitzschia palea* (Kütz.) W. Sm.
39	*Nitzschia umbonata* Lange-Bert.
40	*Nitzschia inconspicua* Grun.
41	*Nitzschia perminuta* (Grun.) Peragallo
42	*Nitzschia desertorum* Hust.
43	*Nitzschia archibaldii* Lange-Bertalot
44	*Reimeria sinuata* (Greg.) Kociolek & Stoermer
45	*Rhoicosphenia curvata* (Kütz.) Grun. ex Rabh.
46	*Synedra ulna* (Nitz.) Ehr.
47	*Thalassiosira weissflogii* (Grun.) Fryxell & Hasle
48	*Bacillaria paradoxa* Gmelin
49	*Encyonema reichardtii* (Kram.) Mann
50	*Luticola goeppertiana* Mann
51	*Pleurosira laevis* (Ehrenberg) Compere
52	*Sellaphora pupula* (Kütz.) Meresckowsky
53	*Staurosira construens* var. *venter* (Ehr.) Hamilton
54	*Diadesmis confervacea* Kütz.
55	*Encyonopsis microcephala* (Grun.) Kram.
	Chlorophyta (green algae)
56	*Cosmarium margaritatum* (Lund) Roy & Biss.
57	*Pediastrum biradiatum* Meyen
58	*Scenedesmus dimorphus* (Turp.) Kütz.
59	*Scenedesmus quadricauda* (Turp.) Bréb.
	Cyanophyta (blue-green algae)
60	*Chroococcus limneticus* Lemm.
61	*Lyngbya* sp. 1 ANS FWA
62	*Oscillatoria limnetica* Lemm.

TABLE 6. Values of macroinvertebrate metrics and periphyton metrics based on all taxa collected for study sites in the Santa Ana River basin, summer 2000.

Station name	Site code	Total taxa	Diatom taxa[a]	Total algae density[a,b]	Diatom density[a]	Biovolume green algae[a,c]	Biovolume blue-green algae[a]	Nitrogen hetero-trophic diatoms (%)	Eutrophic diatoms (%)	Motile diatoms (%)	Intolerant diatoms (%)
		Periphyton metrics									
Cajon Creek below Lone Pine	NN1	33	32	4,137,834	3,304,886	0	0	11	67	37	46
Cucamonga Creek near Upland	NN2	20	20	464,862	464,862	0	0	41	57	27	8
Santa Ana River at upper powerhouse	NN3	17	14	24,557	17,372	0.012	0.001	0	13	33	80
Sunnyslope Creek in regional park	GCH1	23	21	182,898	163,879	0	0.003	29	56	37	7
Sunnyslope Creek near Rubidoux Nature Center	GCO1	23	18	1,156,759	661,704	38.844	0.005	37	41	49	3
Warm Creek near San Bernardino	GCO2	16	13	297,706	132,777	0.002	0.004	3	3	56	0
Cucamonga Creek at Chino Avenue, main channel	UCO1	18	16	365,037	99,372	1.542	0	66	87	81	3
Little Chino Creek above pipeline	UCH1	36	33	463,872	437,527	0	0.006	94	98	27	2
Mill Creek near Splatter S duck ponds	WN1	18	15	8,392,967	3,714,908	1.173	0.778	96	98	85	1
San Timoteo Creek near Eastside Ranch	WN2	13	12	187,230	160,341	0.028	0	84	94	72	0
Santa Ana River at MWD crossing	WN3	20	20	552,316	552,316	0	0.183	94	99	76	0
Santa Ana River below Prado Dam	WN4	32	30	982,102	944,568	0.003	0.012	65	89	84	1
Chino Creek below Pine Road	WCH1	27	23	1,694,796	1,327,293	0.167	0.044	62	66	55	<1
Santa Ana River above Riverside Road	WCH2	20	19	11,635	9,629	0	0.001	74	97	76	4
Chino Creek above Central Avenue	WCO1	23	20	9,575,518	5,764,422	2.691	0.096	96	97	68	<1
Cucamonga Creek at Chino Avenue, wastewater channel	WCO2	12	10	3,040,525	2,836,002	0.862	0.225	100	100	93	0
Cucamonga Creek near Mira Loma	WCO3	15	12	21,056,640	8,722,678	1.547	2.382	99	100	92	0

Station name	Site code	Total taxa	EPT taxa	Trichop-tera taxa	Non-chironomid diptera taxa	Total density[a,d]	Trichop-tera density[a]	Oligo-chaete density[a]	Orthoclad density[a]	Non-insect density[a]	Shredder density[a]	Filterer density	Mean EPA tolerance
		Macroinvertebrate metrics											
Cajon Creek below Lone Pine	NN1	15	6	4	3	22,866	14,375	0	0	2,112	22	10,905	4.8
Cucamonga Creek near Upland	NN2	24	9	4	1	10,500	531	219	0	3,115	1,802	1,742	4.9
Santa Ana River at upper powerhouse	NN3	19	6	4	2	49,147	14,231	0	705	719	353	11,382	5.1

TABLE 6. Continued.

Station name	Site code	Macroinvertebrate metrics: Total taxa	EPT taxa	Trichoptera taxa	Non-chironomid diptera taxa	Total density[a,d]	Trichoptera density[a]	Oligochaete density[a]	Orthoclad density[a]	Non-insect density[a]	Shredder density[a]	Filterer density	Mean EPA tolerance
Sunnyslope Creek in regional park	GCH1	17	5	3	4	48,932	16,092	0	793	6,204	96	15,983	5.7
Sunnyslope Creek near Rubidoux Nature Center	GCO1	17	5	3	4	21,058	889	0	0	11,836	78	56	6.0
Warm Creek near San Bernardino	GCO2	–[e]	–	–	–	–	–	–	–	–	–	–	–
Cucamonga Creek at Chino Avenue, main channel	UCH1	14	1	1	0	31,215	597	16,840	2,743	19,458	2,771	0	7.1
Little Chino Creek above pipeline	UCO1	14	2	2	3	280,347	1,229	23,069	170,273	44,583	170,280	0	7.3
Mill Creek near Splatter S duck ponds	WN1	9	1	1	0	104,597	4,931	17,972	1,656	19,625	828	81,668	6.0
San Timoteo Creek near Eastside Ranch	WN2	11	1	1	2	69,396	728	37,413	11,087	37,938	11,087	1,981	7.3
Santa Ana River at MWD crossing	WN3	20	5	2	2	23,646	13,854	229	667	896	687	14,958	5.3
Santa Ana River below Prado Dam	WN4	8	2	1	0	39,187	31,306	507	5,375	965	2,405	32,583	5.5
Chino Creek below Pine Road	WCH1	5	2	1	0	49,021	40,833	0	2,042	0	2,042	41,243	4.8
Santa Ana River above Riverside Road	WCH2	14	5	2	0	21,925	18,163	199	271	268	320	18,302	5.5
Chino Creek above Central Avenue	WCO1	11	1	0	1	79,285	0	23,681	5,722	41,646	5,722	0	6.1
Cucamonga Creek at Chino Avenue, wastewater channel	WCO2	8	2	1	0	63,403	4,778	16,194	7,681	20,354	7,681	4,778	5.3
Cucamonga Creek near Mira Loma	WCO3	7	0	0	1	388,115	0	267,542	11,760	305,760	11,760	0	6.4

[a] Variable log transformed for statistical analyses.
[b] Periphyton densities are cells/cm^2.
[c] Periphyton biovolumes are $\mu m^3/cm^2$.
[d] Macroinvertebrate densities are organisms/m^2.
[e] –, all macroinvertebrate substrates at this site were vandalized.

Cucamonga Creek (WCO3) (51%), and Warm Creek (55%), but they did not dominate biovolume because of small cell size. Green algae contributed most of the biovolume at two sites, GCO1 on Sunnyslope Creek (95%) and UCO1 on Cucamonga Creek (67%).

An initial CA analysis of periphyton density data exhibited a pronounced "arch effect," indicating that CA did not produce independent ordination axes. The data were reanalyzed with DCA, which corrected this problem. Detrended correspondence analysis resulted in four axes that explained a cumulative 36% of the variance in the data (18%, 11%, 5%, and 2%, respectively). A plot of site scores on the first two DCA axes (Figure 3A) separated least-impacted sites from the other sites. There was no clear pattern related to water type or channel type among the urbanized sites. Most taxa scores were between 0 and 4 on DCA axis 1 and between –1 and 3 on DCA axis 2 (Figure 3B). Five diatom taxa had DCA axis 1 scores less than 0, including *Encyonopsis microcephala* (55), *Cymbella* sp.1 JCK (14), *Navicula cryptotenella* (29), *Encyonema reichardtii* (49), and *Gomphonema kobayasii* (20). Seven taxa had DCA axis 1 scores greater than 4, in-

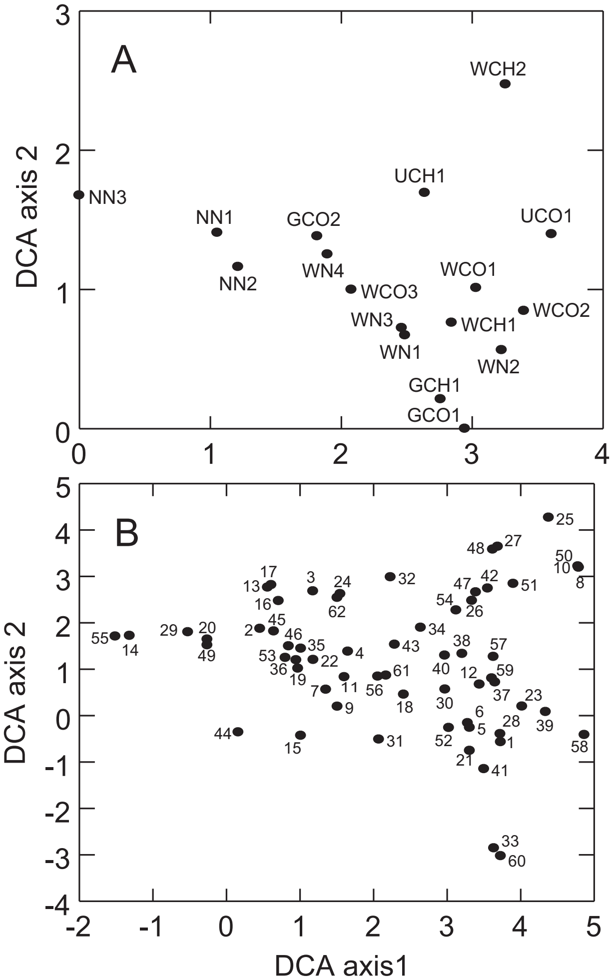

FIGURE 3. Site (A) and algae taxa (B) scores on the first two axes of a detrended correspondence analysis of log transformed periphyton densities from 17 sites in the Santa Ana River basin, summer 2000. See Table 1 for site codes and Table 5 for species codes. The first letter of the site code denotes water source (N, natural; G, urban impacted groundwater; U, urban runoff; W, treated wastewater). The remaining letters denote channel type (N, natural; CH, channelized but unlined; CO, concrete-lined).

cluding six diatoms—*Navicula seminulum* (23), *Nitzschia umbonata* (39), *Navicula decussis* (25), *Luticola goeppertiana* (50), *Caloneis bacillum* (8), *Cocconeis placentula* var. *euglypta* (10)—and one green alga, *Scenedesmus dimorphus* (58). Only three algae taxa had DCA axis 2 scores less than –1, including a blue-green alga, *Chroococcus limneticus* (60), and 2 diatoms *Navicula* sp.1 (33) and *Nitzschia perminuta* (41). Six diatom taxa had DCA axis 2 scores greater than 3, including *Caloneis bacillum* (8), *Cocconeis placentula* var. *euglypta* (10), *Luticola goeppertiana* (50), *Bacillaria paradoxa* (48), *Navicula viridula* var. *rostellata* (27), and *Navicula decussis* (25).

Periphyton DCA axis 1 scores were significantly correlated with 6 of the 14 environmental variables (Table 7) and three periphyton metrics. The significantly correlated metrics were percentage of nitrogen heterotrophic diatoms (r = 0.69, df = 15, P < 0.05), percent eutrophic diatoms (r = 0.60, df = 15, P < 0.05), and percent pollution intolerant diatoms (r = –0.78, df = 15, P < 0.05). All the significantly correlated environmental variables were associated with PCA axis 1 from the analysis of environmental variables (Table 4), suggesting that the correlations were primarily a result of differences between the least-impacted and the urbanized sites. Similarly, significant periphyton metrics are associated with nitrite and nitrate, which was also associated with PCA axis 1 (Table 4). Examination of scatterplots for the univariate correlations (not shown) also suggested this. DCA axis 2 scores were not correlated with any environmental variables and only one periphyton metric, biovolume of green algae (r = –0.49, P < 0.05).

To evaluate the importance of the contrast between least-impacted and urbanized sites to the correlation results, we analyzed the data set with DCA after removing the three least-impacted sites. We then did the same set of correlations using only urbanized sites. None of the correlations were statistically significant.

Benthic Macroinvertebrates

Artificial substrates collected 43 taxa of benthic macroinvertebrates that were present at two or more sites (Table 8). Only data from 16 sites were available because all artificial substrates were vandalized at the Warm Creek site (GCO2). Based on all taxa collected,

TABLE 7. Correlations of algae DCA axis 1 scores and benthic macroinvertebrate CA axis 1 and 2 scores with environmental variables for sites in the Santa Ana River basin, summer 2000. Significant (P < 0.05) correlations are bolded.

Variable	Periphyton DCA axis 1	Benthic macro-invertebrate CA axis 1	Benthic macro-invertebrate CA axis 2
Discharge (m^3/s)[a]	–0.31	0.27	**0.73**
Gradient (m/km)	**0.67**	–0.25	–0.32
Channel width (m)[a]	–0.08	0.23	0.36
Coefficient of variation of bank-full width (%)	**0.65**	**–0.65**	–0.13
Open canopy (degrees)	–0.36	0.43	–0.15
Depth (m)	0.01	–0.01	**0.73**
Coefficient of variation of depth	0.45	–0.23	–0.13
Bed substrate[b]	**0.69**	**–0.56**	0.06
Specific conductance (µS/cm)	–0.43	0.12	0.27
Water temperature (°C)	**–0.72**	0.33	<0.01
Pesticides (number detected)	**–0.59**	0.45	0.24
Nitrate + Nitrite (mg/L as N)[a]	**–0.56**	0.17	0.47
ortho-Phosphate (mg/L as P)[a]	–0.44	0.39	**0.68**
Silicate (mg/L)	0.37	–0.20	–0.20

[a] Variable log transformed for analysis.
[b] The dominant substrate was characterized as: 1, concrete; 2, silt, mud, or detritus; 3, sand (>0.063—2 mm); 4, fine/medium gravel (>2—16 mm); 5, coarse gravel (>16—32 mm); 6, very coarse gravel (>32—64 mm); 7, small cobble (>64—128 mm); 8, large cobble (>128—256 mm); 9, small boulder (>256—512 mm); 10, large boulder (>512 mm), irregular bedrock, irregular hardpan, or irregular artificial surface (Fitzpatrick et al. 1998).

TABLE 8. Benthic macroinvertebrate taxa (with taxon codes) collected from more than one site from artificial substrates in the Santa Ana River basin, summer 2000.

Taxon code	Taxon	Taxon code	Taxon
1	Turbellaria		Helicopsychidae
	Nemertea	21	*Helicopsyche* sp.
2	*Prostoma* sp.		Lepidoptera
3	Nematoda		Pyralidae
	Gastropda	22	*Petrophila* sp.
	Physidae		Coleoptera
4	*Physella* sp.		Dryopidae
	Oligochaeta	23	*Postelichus* sp.
5	Naididae		Elmidae
6	Tubificidae	24	*Optioservus* sp.
7	Arachnida		Diptera
	Amphipoda	25	Ceratopogonidae
	Talitridae		Chironomidae
8	*Hyalella* sp.		Chironominae
	Insecta	26	*Apedilum* sp.
	Ephemeroptera	27	*Chironomus* sp.
9	Leptophlebiidae	28	*Dicrotendipes* sp.
	Tricorythidae	29	*Polypedilum* sp.
10	*Tricorythodes* sp.	30	*Pseudochironomous* sp.
	Baetidae	31	*Rheotanytarsus* sp.
11	*Baetis* sp.	32	*Stempellinella* sp.
12	*Fallceon* sp.		Orthocladiinae
	Odanata	33	*Cricotopus* sp.
	Zygoptera	34	*Nanocladius* sp.
	Calopterygidae	35	*Rheocricotopus* sp.
13	*Hetaerina* sp.		Tanypodinae
14	Coenagrionidae	36	*Ablabesmyia* sp.
15	*Argia* sp.	37	*Pentaneura* sp.
	Anisoptera	38	Psychodidae
16	Libellulidae	39	Simuliidae
	Trichoptera		Empididae
	Hydroptilidae	40	*Hemerodromia* sp.
17	*Hydroptila* sp.		Stratiomyidae
18	*Oxyethira* sp.	41	*Caloparyphus* sp.
	Hydropsychidae	42	*Euparyphus* sp.
19	*Hydropsyche* sp.		Tabanidae
	Psychomyiidae	43	*Tabanus* sp.
20	*Tinodes* sp.		

the total number of taxa present at individual sites varied from 5 to 24 (Table 6). Values for other macroinvertebrate metrics varied widely (Table 6). The number of EPT taxa varied from 0 to 6 taxa. Insects contributed from 69% to 100% of the organisms collected from artificial substrates, except for site WCO3 on Cucamonga Creek (21%), site GCO1 on Sunnyslope Creek (45%), site UCH1 on Little Chino Creek (43%), and site WCO1 on Chino Creek (47%).

The CA analysis of macroinvertebrate density data resulted in four CA axes that explained 57% of the variance (22%, 14%, 11%, and 10%, respectively). The plot of site scores on CA axis 1 separated the sites into two major groups and CA axis 2 separated one of the major groups into two subgroups (Figure 4A). Sites with CA axis 1 scores less than 0 (hereinafter, less-impacted sites) include the least-impacted sites (NN1, NN2, and NN3), two urbanized

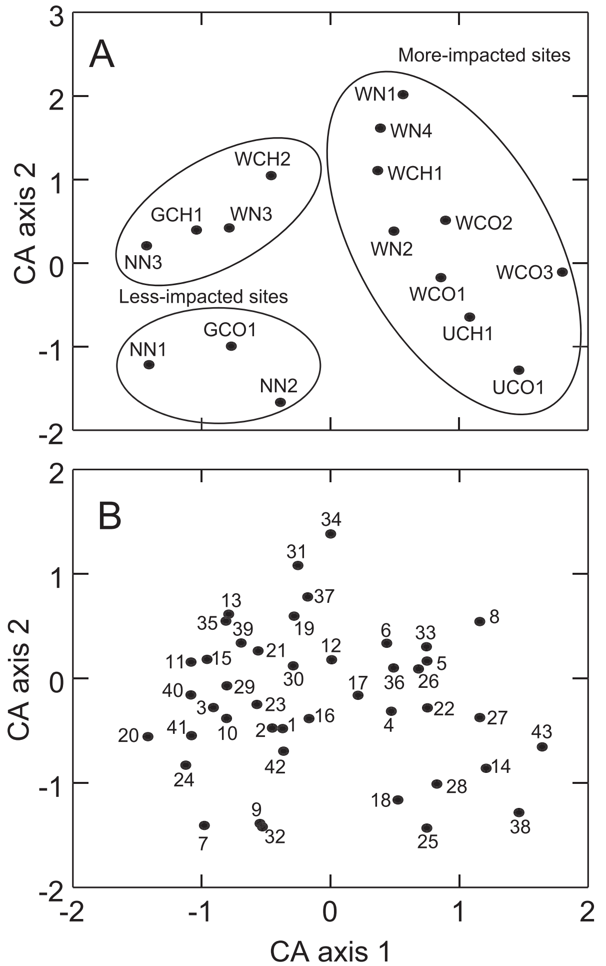

FIGURE 4. Site (A) and macroinvertebrate taxa (B) scores on the first two axes of a correspondence analysis of log transformed macroinvertebrate densities from 16 sites in the Santa Ana River basin, summer 2000. See Table 1 for site codes and Table 8 for species codes. The first letter of the site code denotes water source (N, natural; G, urban impacted groundwater; U, urban runoff; W, treated wastewater). The remaining letters denote channel type (N, natural; CH, channelized but unlined; CO, concrete-lined).

Santa Ana River sites (WCH2 and WN3), and both Sunnyslope Creek sites (GCH1 and GCO1). Sites with scores greater than 0 on CA axis 1 (hereinafter, more-impacted sites) include most sites receiving treated wastewater and all but one concrete-lined channel. Sites with CA axis 2 scores greater than 0 included all the Santa Ana River sites. Sites with CA axis 1 scores greater than 0 appeared to form a continuum along CA axis 2 with no clear breaks (Figure 4A).

Taxa scores on CA axis 1 exhibited a clear break at 0 (Figure 4B), similar to site scores. Taxa with scores greater than 0 were characteristic of the more-impacted sites and were dominated by noninsects and dipterans, many of which are considered tolerant of environmental degradation (Barbour et al. 1999). These taxa included *Hyalella* sp. (8), *Chironomus* sp. (27), *Tabanus* sp. (43), and Psychodidae (38). Taxa having low scores on CA axis 1 were characteristic of the less-impacted sites and tended to be less tolerant of environmental degradation (Barbour et al. 1999). These taxa included *Optioservus* sp. (24), *Tinodes* sp. (20), *Caloparyphus* sp. (41), *Hemerodromia* sp., and *Baetis* sp. (11).

Taxa scores on CA axis 2 exhibited no clear groupings associated with the subgroups of less-impacted sites. The two taxa with high scores (>1) on CA axis 2 were both chironomids, *Nanocladius* sp. (34) and *Rheotanytarsus* sp. (31). Taxa with low scores (<–1) on CA axis 2 were a mixed group, including Arachnida (mites, 7), an ephemeropteran (Leptophlebiidae, 9), a chironomid (*Stempellinella* sp., 32), and two nonchironomid dipterans, Ceratopogonidae (25) and Psychodidae (38).

Benthic macroinvertebrate CA axis 1 scores were significantly negatively correlated with coefficient of variation of bank-full width and bed substrate (Table 7). Both variables were associated with PCA axis 1 from analysis of environmental variables (Table 4). The lack of significant correlations with water quality variables associated with PCA axis 1 suggests that benthic macroinvertebrates were mainly responding to habitat structures. The CA axis 1 scores were significantly correlated with nine macroinvertebrate metrics. These correlations (Table 9) indicated that the assemblages at the more-impacted sites had fewer total taxa, more tolerant taxa, fewer EPT taxa, fewer trichopteran taxa, higher total densities, lower trichopteran densities, higher densities of oligochaetes, and higher densities of orthoclad chironomids (Table 9).

Site scores on CA axis 2 were significantly positively correlated with discharge, depth, and orthophosphate concentration (Table 7). These environmental variables were associated with PCA axis 2 of the environmental analysis, which emphasized differences among urban sites (Figure 2). The CA axis 2 scores were significantly correlated with 3 of the 10 macroinvertebrate metrics (Table 9). The metric correlations indicated that the larger streams had higher densities of filterers but fewer total taxa and fewer nonchironomid dipteran taxa (Table 9).

Similar to algae analyses, scatterplots (not shown) of CA axis 1 site scores with significantly correlated environmental variables suggested that correlations were strongly influenced by the least-impacted sites. The CA was recalculated without the least-impacted sites and the correlation analysis repeated. Positions of the urbanized sites in the site plot (not shown) and of the taxa in the taxa plot (not shown) were very similar to those in the plots using all the sites (Figure 4). There were no significant correlations of CA axis 1 site scores with environmental variables. The same three variables had significant correlations with CA axis 2 site scores (discharge, r = 0.75; depth, r = 0.64; and ortho-phosphate, r = 0.66, n = 13 and P < 0.05 for all). In addition, CA axis 2 was significantly negatively correlated with water temperature (r = –0.57; n = 13 and P < 0.05). The same metrics were correlated with CA axes 1 and 2, except Trichoptera density was no longer associated with CA axis 1 and mean EPA species tolerance was correlated with CA axis 2 rather than CA axis 1.

TABLE 9. Correlations of macroinvertebrate CA axis 1 and 2 site scores with 10 macroinvertebrate metrics for sites in the Santa Ana River basin, summer 2000. Significant (P < 0.05) correlations are bolded.

Metric	Macroinvertebrate CA axis 1	Macroinvertebrate CA axis 2
Number of taxa	**–0.65**	**–0.57**
Number of EPT taxa	**–0.82**	–0.41
Number of trichoptera taxa	**–0.83**	–0.47
Number of nonchironomid dipteran taxa	–0.48	**–0.52**
Total density[a]	**0.71**	–0.15
Trichoptera density[a]	**–0.57**	0.35
Oligochaete density[a]	**0.85**	–0.08
Orthoclad chironomid density[a]	**0.71**	0.42
Noninsect density[a]	0.44	–0.33
Shredder density[a]	**0.86**	–0.03
Filterer density	–0.04	**0.75**
Mean EPA species tolerance	**0.63**	–0.15

[a] Variable log transformed for analysis.

Fishes

Seventeen fish species were collected (Table 10). Only four species are native to the drainage. Fish were captured at 15 of the 17 sites sampled. No fish were collected at the Cucamonga Creek site just downstream of the wastewater discharge (WCO2) or at the San Timoteo Creek site (WN2), which was also just downstream of the wastewater discharge forming the stream. Of 2,242 fish collected, only 696 (31%) were native species. Alien fishes dominated (>66%) most sites.

The cluster analysis identified 5 clusters (Figure 5). The speckled dace cluster consisted of the Cajon Creek site (NN1), the only site where the species was captured. The trout cluster included the other two least-impacted sites. These sites were dominated by rainbow trout, with brown trout *Salmo trutta* also present at the Santa Ana River site (NN3). Urbanized sites formed three clusters with four sites each (Figure 5). The mosquitofish cluster included concrete-lined channels with only western mosquitofish *Gambusia affinis*. The alien species cluster included sites with natural or channelized streams and with three to nine species of alien fishes. The native species cluster in-

TABLE 10. Fishes collected in the Santa Ana River basin, summer 2000.

Scientific name	Common name	Native
Salmonidae		
Oncorhynchus mykiss	Rainbow trout	Yes[a]
Salmo trutta	Brown trout	No
Catostomidae		
Catostomus santaanae	Santa Ana sucker	Yes
Cyprinidae		
Carassius auratus	Goldfish	No
Cyprinus carpio	Common carp	No
Gila orcutti	Arroyo chub	Yes
Pimephales promelas	Fathead minnow	No
Rhinichthys osculus	Speckled dace	Yes
Ictaluridae		
Ameirus melas	Black bullhead	No
A. natalis	Yellow bullhead	No
Ictalurus punctatus	Channel catfish	No
Centrarchidae		
Lepomis cyanellus	Green sunfish	No
L. macrochirus	Bluegill	No
Micropterus salmoides	Largemouth bass	No
Poeciliidae		
Gambusia affinis	Western mosquitofish	No
Poecilia latipinna	Sailfin molly	No
Cichlidae		
Oreochromis mossambica	Mozambique tilapia	No

[a] Rainbow trout are native to the basin but hatchery strains have been widely introduced. The fish captured appeared to be wild, but their genetic heritage is unknown.

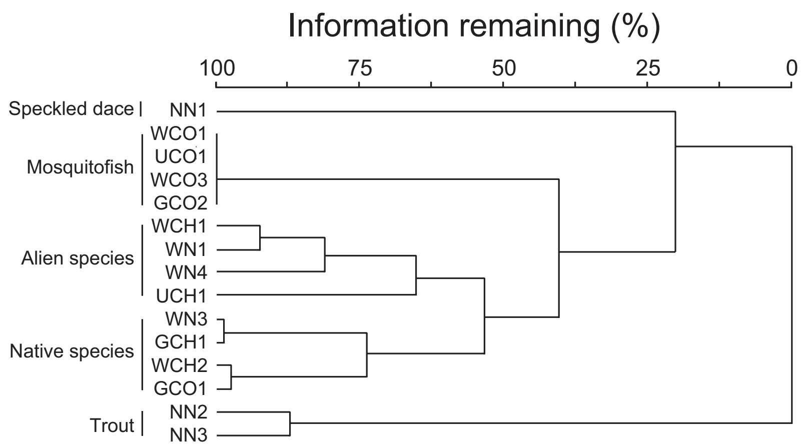

FIGURE 5. Results of a group average cluster analysis of Jaccard similarities for fishes captured at 15 sites in the Santa Ana River Basin, summer 2000. See Table 1 for site codes. The first letter of the site code denotes water source (N, natural; G, urban impacted groundwater; U, urban runoff; W, treated wastewater). The remaining letters denote channel type (N, natural; CH, channelized but unlined; CO, concrete-lined).

cluded sites with various channel and water types and with two to six species of alien fishes but also native arroyo chub. Three sites in the native species cluster also had native Santa Ana sucker (WN3, GCH1, and WCH2).

Analysis of variance was used to determine environmental differences between clusters. The two clusters including only least-impacted sites were omitted from analysis because they were clearly different from the other sites (Figure 2; Table 3). Significant differences were found for coefficient of variation of bank-full width, depth, bed substrate, and water temperature (Table 11). The mosquitofish cluster was clearly different from the others, reflecting that all the sites were in concrete-lined channels. These sites were uniform in shape and substrate and tended to be shallow and warm. The alien species cluster included the deepest most heterogeneous sites with the largest substrates and coolest temperatures. The native species cluster included sites with intermediate depth and bed substrate. Water temperatures were warm, similar to the mosquitofish cluster, but the coefficient of variation of bank-full width was similar to the alien species cluster because both site groups included primarily channelized or natural stream reaches.

Discussion

Biological assemblages of the highly urbanized streams of the Santa Ana basin responded to environmental gradients; however, different taxa showed different patterns. Periphyton primarily differed between least-impacted and urbanized sites. When the least-impacted sites were excluded from the analysis, no relationships were found between periphyton assemblages and environmental variables. Both benthic macroinvertebrate and fish assemblages exhibited associations with environmental variables even when the least-impacted sites were excluded from analysis. Different patterns between taxa are most likely related to different population dynamics.

Periphyton assemblages are well adapted to disturbance (Biggs 1996; Peterson 1996) and can rapidly disperse and recolonize disturbed habitats. Stevenson (1997) provided a theoretical framework for understanding how disturbance and other factors relate to heterogeneity often observed in periphyton assemblages. Dispersal ability is an important factor in this framework and is likely important in the Santa Ana River basin. Many algae species and other microorganisms, including small invertebrates, are widely distributed on large geographic scales because of wind dispersal of the organisms or specialized resting stages (Kristiansen 1996; Finlay 2002). Other likely dispersal mechanisms (Kristiansen 1996) within the Santa Ana River basin include downstream drift; intermittent connections with more permanent bodies of water such as detention, fishing, or water treatment ponds; and external and internal transport by wading birds, which are common even in concrete-lined channels. Although there is disagreement concerning the ubiquity of algae and other microorganisms at large geographic scales, such as continental and global distributions (Kociolek and Spaulding 2000; Hillebrand et al. 2001; Finlay 2002), it seems likely that all species have an equal probability of colonizing available habitat within the Santa Ana River basin.

Other studies have noted differences in the structure of periphyton assemblages between rural and urban land uses (Sonneman et al. 2001; Winter and Duthie 1998, 2000); however, similar to our study, Sonneman et al. (2001) did not find any strong patterns of periphyton assemblage composition when only urbanized sites were considered. In the Santa Ana River basin, when the least-impacted sites were excluded, nutrient concentrations did not appear limiting with detectable nitrite + nitrate available at every site and ortho-phosphate available at all but three sites (Table 3), presumably because of the dominance of treated wastewater. Similarly, most sites were quite open, so light was not a limiting factor. Thus, the particular taxa colonizing artificial substrates at a particular site

TABLE 11. Means (±SD) for variables with significant differences between fish site clusters for sites in the Santa Ana River basin, summer 2000. Different letters indicate groups significantly different in subsequent Tukey pairwise tests.

	Fish site cluster		
Variable	Mosquitofish	Native species	Alien species
Coefficient of variation of bank-full width (%)	1.5 ± 3.0 A	15.1 ± 10.0 B	20.7 ± 5.5 B
Depth (m)	0.06 ± 0.03 A	0.18 ± 0.06 A,B	0.40 ± 0.19 B
Bed substrate	1.0 ± 0.0 A	3.0 ± 1.1 A,B	4.4 ± 1.2 B
Water temperature (°C)	29.5 ± 1.8 A	28.9 ± 2.4 A	23.9 ± 0.5 B

were likely the result of random colonization and available taxa pool rather than a response to water or habitat quality. Interestingly, a metric approach to the data (Burton et al. 2005) suggested that the periphyton assemblage did respond to water source and channel type, within the urbanized subset of sites. This suggests that urbanization of stream environments creates conditions suitable for taxa with certain environmental optima but that the particular taxa having those characteristics at any particular site are determined by random colonization.

Macroinvertebrates appeared primarily responsive to habitat structure. Correlations of the primary gradient in assemblage structure (CA axis 1) with coefficient of variation of bank-full width and bed substrate (Table 7) suggest differences in macroinvertebrate assemblages related to stream channelization (low coefficient of variation of bank-full width) and concrete lining (low values for bed substrate). Correlations with the biological metrics suggest that the main difference in macroinvertebrate assemblages was a loss of EPT taxa, mainly trichopterans, at the more urbanized sites (more-impacted sites in Figure 4). The urbanized sites also tended to support more tolerant taxa. These metric results are consistent with other work documenting the effects of urbanization on stream macroinvertebrates (Walsh et al. 2001; Morley and Karr 2002; Wang and Lyons 2003). The grouping of several urbanized sites with the least-impacted sites (less-impacted sites in Figure 4) suggests that urbanized sites are capable of supporting relatively "natural" macroinvertebrate assemblages. Even the least-impacted sites can be quite stressful because of high water temperatures and low flows during the summer. Many native macroinvertebrates are likely tolerant of environmental stresses and could survive in urban streams if favorable habitats were available. In the analysis excluding least-impacted sites, the absence of correlations between CA axis 1 and the environmental variables makes it difficult to hypothesize about the specific conditions supporting more natural assemblages.

Correlations between the secondary gradient in macroinvertebrate assemblage structure (CA axis 2) and discharge, depth, ortho-phosphate, and water temperature, whether or not the least-impacted sites were included in the analysis, likely reflect a response to stream size. Discharge was greatest at sites supplied with treated wastewater and both depth and orthophosphate were correlated with discharge (Table 4). These results are similar to those of Burton et al. (2005). Although we did not measure variation in stream flow directly, discharges of treated wastewater are one of the more consistent sources of water to these urban streams. Interactions between dispersal ability and permanence of flow may be important in the ecology of these streams. Dispersal ability can vary widely among aquatic macroinvertebrates, with important implications for population structure (Meyers et al. 2001; Miller et al. 2002; Rundle et al. 2002). Consistent wastewater flows may provide stable habitat for poor dispersers and a source of colonizers to more ephemeral habitats. Although this topic has not been addressed in urban streams, studies of aquatic macroinvertebrate dispersal between desert springs (Meyers et al. 2001; Miller et al. 2002) and dispersal of terrestrial macroinvertebrates between habitat patches in urban areas (Wood and Pullin 2002) provide useful models for pursuing such questions.

Exceptions to the general patterns of association between macroinvertebrate assemblages and environmental variables were largely due to site specific factors. The similarity of the Sunnyslope Creek site GCH1 to the least-impacted sites was not surprising because the channel and setting (a regional park) were fairly natural. The similarity of the upstream concrete-lined channel (GCO1) was more surprising but is understandable given the specific site conditions. The groundwater source at this site is apparently fairly constant and the lack of recent storm flows had resulted in accumulation of dense beds of filamentous algae and areas of fine substrate that had allowed emergent plants to grow within the concrete channel. The combination of complex habitat and a nearby, fairly natural source of colonists (GCH1) resulted in a macroinvertebrate assemblage similar to the least-impacted sites. The inclusion of the Santa Ana River above Riverside Road (WCH2) probably occurred for similar reasons. This site is located downstream of several wastewater treatment plants that supply a steady source of water and the channel, although very straight, had large amounts of gravel substrate in addition to sand. Thus, this site also represents a structurally complex, perennial habitat. The other Santa Ana River site (WN3) in this group is the most anomalous. The site is downstream from WCH2 so has similar hydrologic characteristics, but the channel is dominated by sand. There is some habitat complexity due to aquatic macrophytes and small amounts of gravel and woody debris. The main reason for the similarity between these two Santa Ana River sites may simply be downstream drift from one to the other.

Fish distribution in the basin exhibited several interesting features. Restriction of rainbow and brown trout to the least-impacted sites was expected. Water temperatures at urban sites were high enough to cause severe stress or even acute mortality of trout (Moyle 2002). The limited distribution of speckled dace was expected based on earlier descriptions of the distribution of this species in the region (Swift et al. 1993); however, the reasons for the limited distribution are unclear. Swift et al. (1993) suggested that appropriate habitat for this species has always been limited in Southern California.

Fish distribution among the urbanized sites was clearly associated with environmental conditions. Western mosquitofish was the only fish found in three of the four concrete-lined channels. This species is widely used for mosquito control and is actively planted by mosquito control agencies. The species is tolerant of high temperatures and low-dissolved oxygen (Moyle 2002). Its small size, omnivorous feeding habits, rapid generation time (3–4 generations per year), and the fact that it is a live-bearer make it the only species that can complete its life cycle in the shallow, homogeneous habitat of concrete-lined channels, which also lack appropriate spawning habitat for the other species (Moyle 2002). The only exception was the concrete channel on Sunnyslope Creek, which supported additional species but actually had fairly complex habitat as described above.

In the context of fish conservation, the ability of some highly urbanized streams to support native arroyo chub and Santa Ana sucker is important. Sites supporting these native species were similar to other sites in most characteristics; however, there were differences for coefficient of variation of bank-full width, depth, bed substrate, and water temperature. Rather than having the highest or lowest values for these variables, the sites with native fishes tended to be intermediate. Neither native species can complete its life cycle in concrete channels because appropriate spawning habitat is absent (Moyle 2002). The reasons for their absence from the other sites is unclear. The sites where the species were found included the Santa Ana River (WN3 and WCH2) and Sunnyslope Creek (GCH1 and GCO1). The occurrence of Santa Ana sucker may simply reflect that gravel in the area around WCH2 provides the best spawning habitat in the region (Moyle 2002) and that populations downstream in the Santa Ana River and nearby Sunnyslope Creek are dependent on this successful spawning for recruits. All four sites are within 10 km of each other and are hydrologically connected. This explanation does not hold for arroyo chub, which can also spawn over fine substrates or plants. Moyle (2002) indicates that arroyo chub does not do well in the presence of alien species and similar observations have been made for Santa Ana sucker. Many of the alien species typically inhabit deeper, slower moving waters in their native habitats (Moyle 2002). The intermediate depths and perhaps other unmeasured characteristics of the sites with native species may favor native species over alien species. These results suggest that urban streams in the Santa Ana River basin can be configured to help in the conservation of native fishes.

Our study shows considerable variation in macroinvertebrate and fish assemblages of highly urbanized streams associated with variability in the environmental characteristics of those streams. Although not measured directly, the reliability and quantity of flow is likely an important environmental variable in this system. Of interest to managers is that treated wastewater, a reliable source of water in urban systems, appears to support valuable aquatic resources, including a threatened fish species. However, caution is warranted given concerns about the endocrine system disrupting effects of some chemicals often found in such waters. Any improvement in a specific habitat condition (e.g., water quality) for fish assemblages can be more than offset by habitat degradation caused by other human actions (Limburg and Schmidt 1990). For example, Trimble (1997) called for erosion control measures to protect property affected by increased rates of erosion due to urbanization. All too often, such measures have emphasized engineering solutions, such as channelization and concrete lining, which degrade the ecological and esthetic value of urban streams. Management should address all aspects of the environment simultaneously.

The study of urban systems provides ecologists the opportunity to observe the effects of intense rural-urban environmental gradients on ecological communities (McDonnell and Pickett 1990). Such studies provide opportunities to address basic ecological concepts such as disturbance, species invasions, and the effects of environmental stress. Similarly, Grimm et al. (2000) argue that ecological research in cities provides opportunities for advances in theoretical ecology and for the integration of ecological and social sciences. Continued study of urban streams in the Santa Ana River basin and elsewhere will help elucidate the fundamental principles of stream ecology and help develop the applied knowledge to conserve the ecological values of all streams as human populations continue to grow.

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